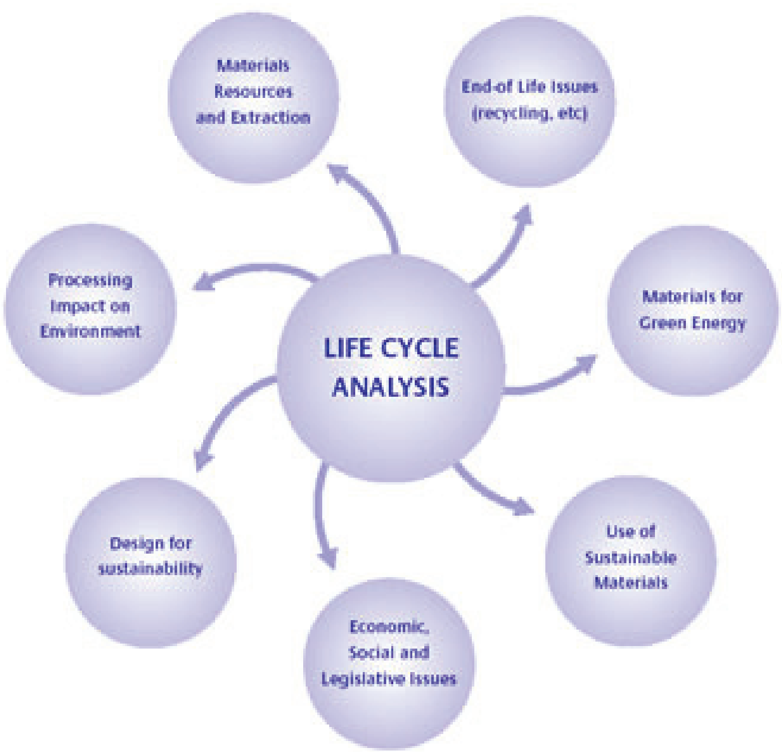
Life Cycle Assessment

Ashleigh Powell and Brad Singer



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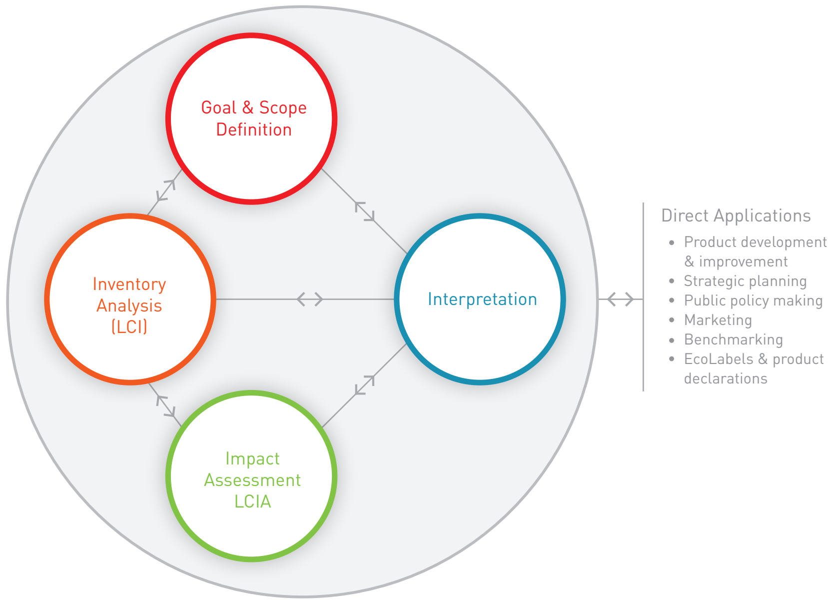

Fig. 01 The Life Cycle Assessment framework.

Introduction

Life Cycle Assessment (LCA) represents an emerging methodology aimed at comprehensively evaluating the environmental impacts of products, processes, or services during their life cycle. The term life cycle is synonymous with the concepts "cradle to grave" or "cradle to cradle" and describes the complete life span, from manufacture, use and maintenance, to final disposal or reuse.[1] By comprehensively evaluating environmental parameters, Life Cycle Assessment aims to generate a "more accurate picture of the true environmental trade-offs in product and process selection."[2] Thus, the primary purpose of conducting a LCA is to, "better inform decision-makers by providing a particular type of information (often unconsidered), with a life cycle perspective of environmental and human health impacts associated with each product or process."[3]

As the consequences of mankind's impact on the natural world have materialized, Life Cycle Assessment has gained significant momentum and complexity in theory, application and purpose. Conceptualized in the 1960's in response to concerns over depleting natural resources, the evolution of LCA has followed a progressive trajectory and paralleled developments in the field of environmental science and the emergence of computer-based technologies. Central to its development, have also been the efforts of national and international bodies to unify acceptable methodologies for carrying out comprehensive environmental accounting processes. In 2006, the International Organization for Standardization (ISO) published the currently accepted principles and framework for Life Cycle Assessment. The LCA Standard is referred to as ISO Standard 14040:2006 and presents a "systematic and phased" process

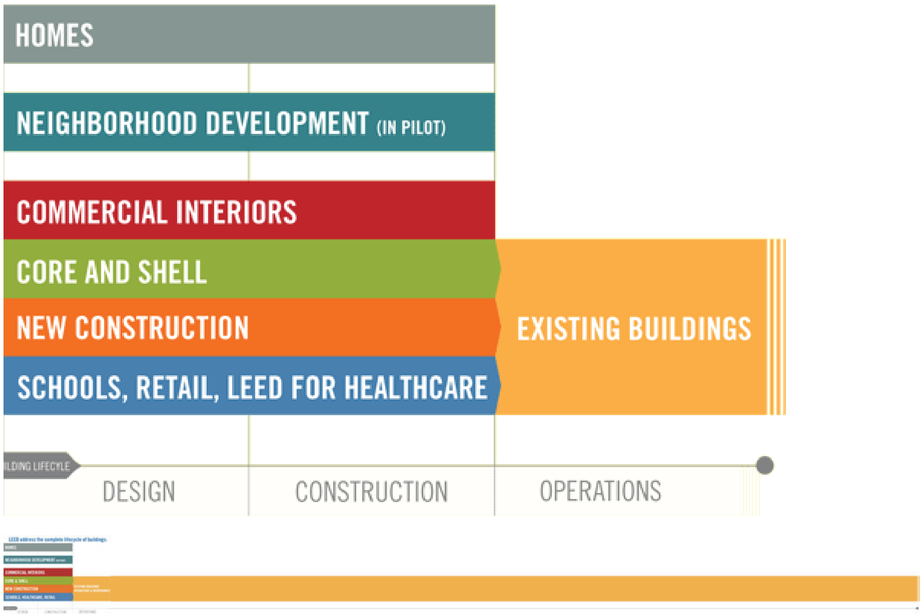

Fig. 02 The scope of building operations relative to the initial design and construction.

consisting of: goal and scope definition, inventory analysis, impact assessment and interpretation.[4] Applied collectively, these four phases are intended to reveal underlying environmental, economic and human health impacts and discourage “problem-shifting… from one phase of the life cycle to another, from one region to another, or from one environmental problem to another.”[5] While “many methodological problems remain unsolved”[6] analysts have stated that the adoption of an international standard has, “increased the maturity and methodological robustness of LCA.”[7] (Fig. 02)

The combined theoretical and technical potential of LCA has influenced the current political climate in which political mandates for quantitative reductions associated with natural resource depletion and greenhouse gasses have emerged. Most notable, is the Executive Order for Federal Leadership in Environmental, Energy, and Economic Performance issued by President Obama on October 5, 2009. This Order, “requires agencies to measure, manage, and reduce greenhouse gas emissions” by specific percentages and associated dates. Suggested strategies include efforts to, “increase energy efficiency; reduce fleet petroleum consumption; conserve water; reduce waste; support sustainable communities; and leverage Federal purchasing power to promote environmentally-responsible products and technologies.” Thus, it is evident that in order to meet the targets outlined by this Executive Order, current LCA methodologies will be required to adapt and subsequently continue to mature.

What do the current stages of LCA offer and what are the primary challenges the process poses for quantifying and analyzing environmental impacts? A review of the four phases of the ISO Standard will provide insight on what is required of LCA in order to meet its potential to provide a comprehensive environmental performance analysis.

Goal and Scope

Goal and Scope refers to the foundational phase of the LCA process that defines the, “reasons for carrying out the study, the intended application, and the intended audience.” [8] Serving as a navigator for the subsequent phases, the decisions outlined during the goal and scope phase, “guide the entire process to ensure that the most meaningful results are obtained.” [9] Questions practitioners answer during this process concern, “what type of information is needed to inform the decision-makers; the required specificity for the study; how the data should be organized and the results displayed; the overall scope of the study, and the ground rules for performing the work.” [10] While seemingly straightforward, the success of the following phases as well as the integrity of the overall results relies on a strong foundation established during this initial phase.

Life Cycle Inventory

During the Life Cycle Inventory (LCI) phase, “all the energy, water, and materials flowing into and out of every process in the subject’s life-cycle—including pollutants—are quantified and categorized” [11] In other words, this phase describes the process of collecting data to reveal numerical values associated with inputs (energy, water and materials) and outputs (environmental/atmospheric emissions, waterborne waste, and solid waste). Ideally, this phase will result in a clear and detailed numerical summary that reveals the "comparative environmental impacts" resulting during the entire life cycle of a product, process or activity.[12]

However, inherent within this phase are assumptions and limitations that result from the availability of data. In the United States, this challenge has been recognized as one of the primary obstacles to overcome in order to perform legitimate life cycle assessments. In order to address this, the United States Department of Energy (DOE) published a plan in August of 2009, aimed at developing a U.S. LCI Database which will provide "publicly available, high-quality U.S.-based LCI data that (is) comprehensive, transparent, and critically reviewed."[13] Adding integrity to the database will hopefully result in reduced assumptions resulting from times when, "factual data either cannot be obtained within the context of the study or do not exist." [14] Until then, life cycle assessments are subject to interpretation based on the "quality, accuracy, and collection methods" of data.[15] (Fig. 03)

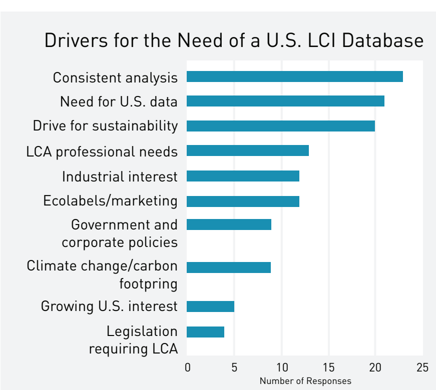

Fig. 03 Drivers for Life Cycle Assessment and Life Cycle Inventory Data.

Life Cycle Impact Assessment

Life Cycle Impact Assessment (LCIA) refers to the process of correlating the LCI data with environmental impacts such as: global warming, ozone depletion, ecosystem toxicity, acidification, diminished human health, and resource depletion. Thus, during the LCIA phase, the complex life cycle inventory data is harmonized with similarly comprehensive environmental science data. While the overall intention is to rank environmental and human health risks in order to inform the best decision, "It is not uncommon for LCA studies to omit some of (the) impact categories from their scope, either because it is not feasible to collect the relevant inventory data or because the science for translating inventory to impacts is not considered reliable."[16] As a result, the LCIA phase relies heavily on transparency when reporting results. If assumptions were made or "weighting" occurred (valuing some impacts over others), the analysts are encouraged to be forthright with their decisions and methods. Again, this speaks to the integrity and reliability of the overall Life Cycle Assessment.

Life Cycle Interpretation

The goal of this final phase is to, "analyze results, reach conclusions, explain limitations, and provide recommendations" all while continuing to maintain the transparent nature that is essential to the integrity of the overall study.[17] By presenting an open and critical analysis of the findings, applicants are empowered with the necessary information to make informed decisions.

Each stage of the LCA, presents various challenges and opportunities for assessing the environmental impact of a product, process or system. As the complexity of the defined goal and scope increases, so too does the overall assessment. Larger parameters, such as a whole building versus an individual product, exemplify this challenge. Subsequently, LCA applied to buildings is evolving in various ways. The next segment will review some of those developments and methodologies.

Our Understanding of Building

The core objective of Life Cycle Assessment of buildings is gaining a holistic understanding of energy flows so new generations of buildings can be improved based upon learned, practical knowledge. This implies an embarrassing flaw: the building industry does not have a full understanding of the buildings they produce. Technological advances of the twentieth century have outpaced the architect's ability to index the inter-workings of the built environment. We are at the brink of gaining an understanding of resource depletion and energy expenditure associated with buildings, making it possible for architects to learn from their buildings as they once did.

Consider a traditional European village, for example. (Fig. 04)

Fig. 04 19th century European village.

The builders were restricted to local material resources, allowing them to become intimately familiar with the materials over time. Like an organic being, the building's form was the manifestation of its function. If the building did not perform well, the direct and honest nature of its construction would expose inappropriate decisions. The builders were accessible to everyone because they lived near and sometimes in the buildings they created. Local design knowledge would accumulate and be shared by the community so that all builders could advance their knowledge and therefore their buildings.[18]

The Current Building Landscape

Culturally, we value the results of learning more than the process itself. Logically, results cannot exist without process, yet we market our buildings as finished products in exchange for consumer confidence. If the building industry does not present the need for monitoring, research, and improvement, it is perceived that the industry produces mature products. Ironically, this mindset prohibits advancement and therefore the creation of a mature product. What the built environment is left with are prototypes--the first inception of a unique idea--posing as refined, mature works. To move from prototype to mature product, capital, time, and research must be invested, and clients as a whole are not currently interested in this investment. During the twentieth century, other industries have advanced faster than the building industry by investing in research. To compensate for lack of research and poor design, the building industry masks its flaws at the expense of economic and ecological resources.

Buildings today are the product of fragmented specializations, each protective of their knowledge for self-preservation. The high complexity of buildings requires specialists, but that does not mean they cannot collaborate as one instead of working in paralleled isolation. Challenges are addressed in isolated sections instead of holistically, and the final product is a collection of packaged answers instead of a gestalt of layered solutions. Reasons for this include complexity, liability and self-preservation of one's knowledge niche. The more distance the creators of buildings have from their works, the more necessary it is for users (via feedback) to influence the creators.[19]

Another reason for architects not having a holistic understanding of their works is that they view buildings as static objects with a precise function. Architects fail to recognize buildings as dynamic entities, affected by their users and time. The user will deviate from the assumptions made at the inception of the design. The more deviation from the presupposed program, the more the building is not successful. Like human beings, buildings need to develop over time to mature, grow, and evolve to prevent deterioration. Stewart Brand talks about "blue jeans buildings"--buildings that age honestly and elegantly with time. This requires acceptance of a building as an evolving entity where the design and construction phase is just the start of a long process over the life of the building.[20]

The lower cost, complexity, and variables comprising pre-twentieth-century buildings facilitated a rapid feedback loop between builders and their buildings. A high level of technological sophistication required for contemporary buildings has distanced us from our ability to monitor and learn. This makes for a higher initial investment and a much more difficult product to diagnose, monitor, and improve--merely creating the complex object is a feat in itself, and the industry seems to be content with that. Today, half of overall building cost is their systems--elements that are literally hidden behind walls. From the point of view of the architect, this also means that half of the overall understanding of the building is hidden behind specialists. Just a century ago, "systems" elements of buildings was only 5% of the project cost (e.g. some electrical wire or heating stove), allowing all factors to inform and be informed by the gestalt, making for a continuity of vision throughout the design to better serve its users.

A Lost Culture of Life Cycle

Resource mining and construction techniques have made creating buildings a relatively inexpensive endeavor. Until a century ago,

Fig. 05   The Driskill Hotel in Austin from 1900's to present.

Fig. 06   6th Street in Austin from 1970 to present.

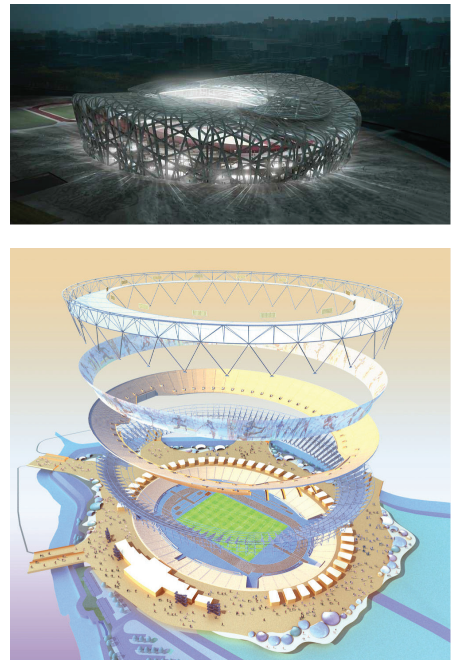

Fig. 07   Beijing and London Olympic Stadiums.

the gathering of resources and construction of buildings was done without automation, requiring a large investment in labor. This inherently caused the generations prior to think of buildings as long-term investments. Since the buildings were literally set in stone with the intent on future generations to use, the builders took great pride and craft in their work. The buildings were the manifestation of an investment in society. Future generations would use and learn from this practice, thinking long-term with their creations for the addition of the collective memory and betterment of the whole. (Fig. 05)

Over time, the social role of the building may have changed, but the building and its social ideology remained as solid as its construction. Density was key to creating buildings that would be desired decades into the future by the convenience of being next to other buildings with public access. Many downtowns throughout the United States were built a century ago, and as a result of creating high quality buildings in dense locations they are still standing today. However, almost all are successfully serving a different client with different programs than originally designed for. The flexibility provided by buildings downtown have allowed different programs to utilizes the space without having to tear down and build anew to accommodate a specific function--there is a mediation between the building stock and program instead of the building conforming strictly to the (short-term) program. (Fig. 06)

Our contemporary building culture creates buildings that are strictly suited for the initial buyer at the expense of not easily accommodating future use. "Planned obsolescence" meant that buildings would be created for a specific program for a specific period of time instead of being an investment that would be attractive to future buyers. There are intelligent ways to recognize planned obsolescence, such as anticipation and scaling method exhibited by the London Olympic 2012 stadium. (Fig. 07) However, most projects do not plan beyond the initial snapshot view of a building's function, exchanging short term luxury for long term ecological and economical consequences.

Building Evolution

For a building to lead a long life, it must adapt to its conditions in the same way a living creature does. Failure to do so reduces efficiency of the overall building stock. Life Cycle Assessment is the consideration of energy flows over time, including how those flows may evolve. If designers fail to anticipate future users, at best the users will be forced to struggle with problems, and at worse the building will be destroyed and replaced. To design evolving buildings, we must first learn from the evolving building stock.

To gain a dynamic understanding of a building throughout its life, architects must monitor buildings instead of simply planning them. Rapid feedback is the key to learning, adapting, and improving.[21] After performing a surgery, a doctor monitors the patient to ensure maximum recovery and to learn from their experience for future patients. Currently, architects act as surgeons who never follow up on their patient's progress after a procedure. Inherently, contemporary buildings are complex, static objects which do not easily respond to amending. The owner, just having experienced major surgery, is not interested in paying for more medical attention, and both parties simply hope for the best thereafter. A desire to learn from buildings and to establish feedback loops that will inform their future designs can instill a culture of respect for users, continuous learning, and improvement loops.

Enriching Client Values

All approaches for maximizing the long-term effectiveness of a building require a higher initial investment. This is difficult to achieve in a culture fixated on low initial investment with the quickest possible return. The problem of Life Cycle Assessment extends beyond execution and into implementation.

For most clients today, the bottom line is simply the sum of all the building elements. When architects design buildings as a collection of independent components, the clients are correct in their assumption. Buildings must be designed holistically with all components working in unison, making for projects that depend on parts that cannot be "value engineered" out. Architects must educate the owner that their building is an investment, which can be passed on for return. The more value imbued into the investment, the more competitive it will be in the marketplace. The question becomes for the client, not "When do I get my money back?" but rather "How well is my money working for me?" Investing in long-term thinking will assuredly return a profit due to energy prices rising faster than inflation.[22]

Investing a high amount into the built environment offers payback not only in energy flows, but also from occupant satisfaction. While achieving a certain LEED rating alone will not automatically reduce overall cost, the impact it has on the productivity of its inhabitants is significant. For example, office workers who work in a comfortable environment are more productive and are sick less often. Merely a 1% increase in productivity covers the cost of a higher initial investment because workers are the highest expense of any office environment.[18.1]

Methods of Learning

The sophistication of buildings requires feedback that extends beyond simple monetary and energy use. Recent methods of learning include:

Interdisciplinary Design: The segmented specialties required to produce today's complex buildings often operate in parallel. The result are buildings that do not cohesively address the specific needs of a particular project as well as they could, from user comfort to energy use. Interdisciplinary design converts parallel building channels into lines of communication so that a building can perform better for the client and environment.

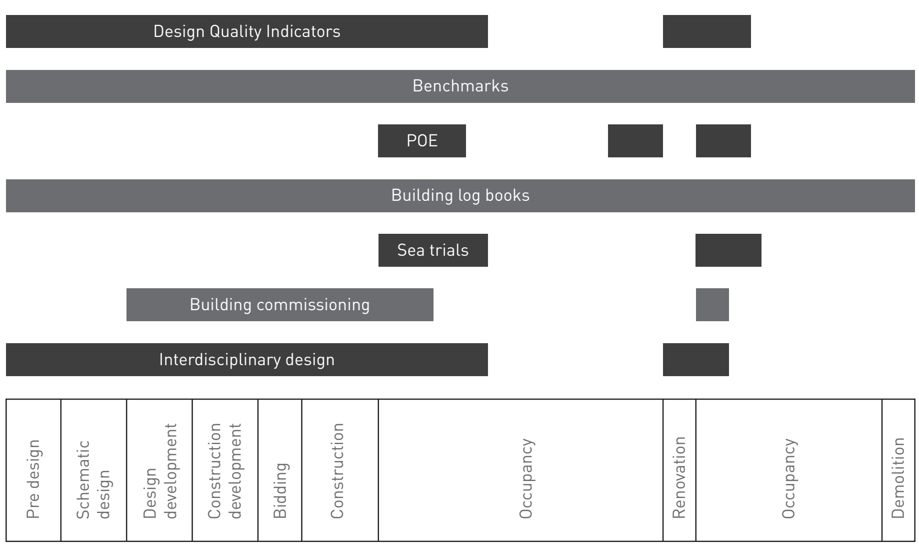

Fig. 08 Methods of learning from buildings and their appropriate time for implementation.

Full Building Commissioning: Many buildings go through their life with poorly functioning systems, operating at below their specified levels of performance. Many performance problems that occur in green buildings are linked to poorly performing building envelopes and could be avoided by proper commissioning procedures. Full Building Commissioning physically verifies the design models.

Building 'Sea Trials': Buildings are unique and need to be treated as such. Building 'Sea Trials' is a period of fine-tuning after construction is finished, where the design team is involved in running the building for the first period of operation.

Building Log Books: Medical patients have associated files that which log their history and warn of complications. Building Log Books would record performance over time and inform decisions regarding the modification of the building in the future. At the end of the life of the building the information on specifications of structural, HVAC and other components will help to enable them to be more easily reused.

Post Occupancy Evaluations: An examination of the effectiveness for human users of occupied design environments. The inhabitants complete surveys to inform both design and building management.

Design Quality Indicators: DQI have been developed in the UK to provide a tool kit for improving the design of buildings by capturing perceptions of design quality embodied in buildings. Attributes measured include functionality, build quality, and impact.[23]

Building Information Modeling (BIM)

Life cycle has always been a peripheral concern of environmentally responsible designers, but only now with the assistance of computers can we gain an accurate, holistic view of building life cycle. Building Information Modeling allows designers to build a virtual prototype of the building in the computer. BIM catalogues objects that have embedded information instead of simply modeling in 3d.

All of the components in the virtual prototype can be indexed, analyzed, and tested to ensure the best combination of products comprise the building.

BIM brings together the factioned camps of specialization with interoperability. An architect can generate a basic form and in parallel a mechanical engineer can place HVAC equipment, with both responding to each other. It's the equivalent of drawing on the same piece of paper in real time, despite not being in the same physical location. The computer prototype can then be viewed by all specializations for feedback that extends one's boundaries. (Fig. 09 - 11) [24]

Building Energy Simulation (BES)

In addition to BIM, building energy simulation software is now at a state to make the sophisticated calculations regarding environmental performance. (Fig. 12)

BES is generally recognized as providing the best means of comparing the energy ramifications of building design alternatives. However, BES should not be regarded as being a guarantee in predicting future energy consumption of a building. BES programs are generally organized into three major sections:

Building Loads: Calculates the heating/cooling required to keep the rooms/zones at the temperatures desired by the occupants

Air Handling Systems ("Systems"): Calculates the energy required to move the heating/cooling (calculated in the Loads section) around the building

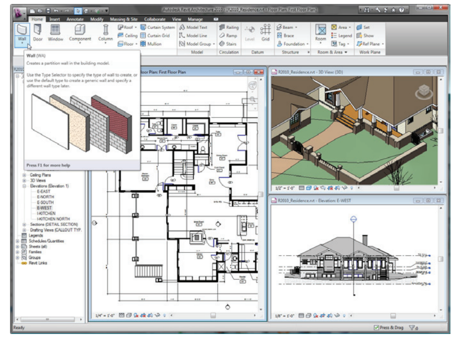

Fig. 09 Revit Architecture creates a prototype for testing.

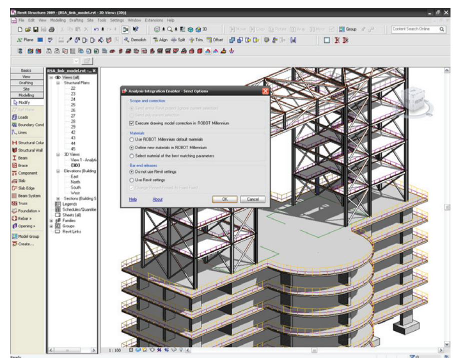

Fig. 10 Revit Engineering modeling structure..

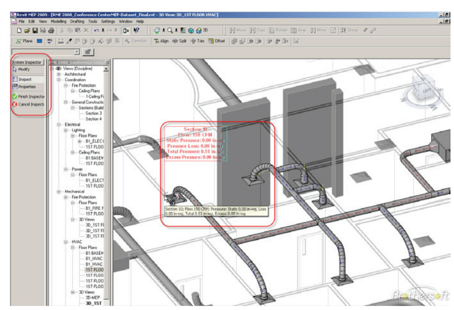

Fig. 11 Revit Engineering displaying duct locations.

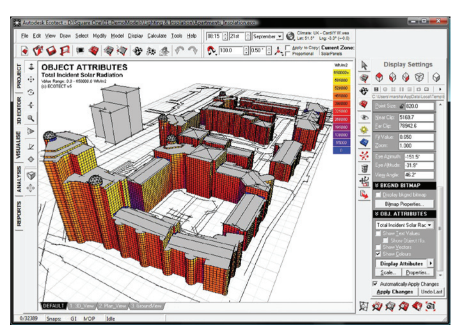

Fig. 12 Ecotect mapping insolation levels on building faces.

Central Plants: Calculates the fuel required (and resultant cost) to produce the heating/cooling requirements calculated in the Systems section. [25]

LCA Calculation

Unlike structural or mechanical loads that must be calculated to the fullest extent for client satisfaction, the impact a building has throughout its lifecycle is currently of no consequence to most clients. This means that most clients will not fund a calculation of lifecycle impact, and therefore the architect cannot afford to spend extra time performing these operations. The result is buildings that use more embodied energy than necessary initially and throughout its lifecycle.

The cavalier view held by most developers concerning the environmental impacts of their buildings is not likely to change as rapidly as the situation is dire. Software now available to the architect can keep track of building data near-automatically in the background. With minimal extra work, the architect can gain a full understanding of the impact the future building will have throughout its life.

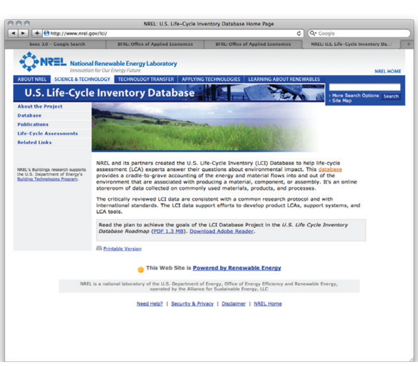

Fig. 13 NREL's Life Cycle Inventory Database.

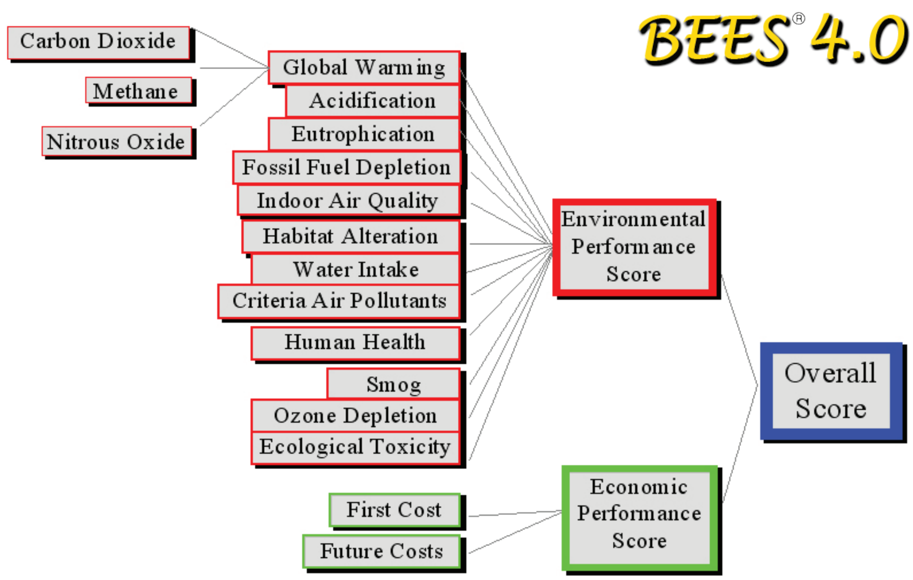

Fig. 14 The scope of the BEES model includes enconomic as well as ecological factors for feasibility of implementation.

Life Cycle Inventory Database

Software on the user-end is not the only aspect making lifecycle assessment feasible today. Like the value of currency, a universal consensus of the ecological impact of building components must be reached. This data must be regulated, verified, and made freely available. The mass-communication and real-time nature of the Internet allows the ecological impact of building components to be instantly available and updated. Only now with prevalence of the Internet can a universal database of building components be updated frequently by the manufacturers and utilized by designers in a rapid and accurate fashion.

The National Renewable Energy Laboratory (NREL)'s U.S. Life-Cycle Inventory (LCI) Database serves as the primary resource for lifecycle assessment software. (Fig. 13) This database "provides a cradle-to-grave accounting of the energy and material flows into and out of the environment that are associated with producing a material, component, or assembly." [26] The data is critically reviewed and consistent with common research protocol with international standards.

LCI of Building Components

The software tools available for life cycle assessment are designed for the different stages of the design process. For comparing products at the specification or procurement phase, BEES (Building for Environmental and Economic Stability) is the most widely used software and was developed by NIST's (National Institute of Standards and Technology's) Building and Fire Research Laboratory. [27] The BEES model is valuable for designers in that it gives a single score inclusive of economic performance along with ecological performance. (Fig. 14) This allows designers to quickly compare products without having to calculate the cost-benefits themselves. The inclusion of economic data makes sustainable building practices more tangible to clients who may otherwise be too skeptical because of uncertainty.

LCI of Building Assemblies

At the conceptual design stage, the ATHENA Environmental Impact Estimator (EIE) software is the leading analyzation tool for whole buildings and assemblies. A range of indicators without weighting is generated to show environmental effects of changes in shape, design, or material make-up of buildings. [28]

The Estimator takes into account the environmental impacts of:

- -Material manufacturing, including resource extraction and recycled content
- -Related transportation
- -On-site construction
- -Regional variation in energy use, transportation and other factors
- -Building type and assumed lifespan
- -Maintenance, repair and replacement effects
- -Demolition and disposal
- -Operating energy emissions and pre-combustion effects [29]

Although the Estimator does not include the operating energy simulation capability, it does not allow users to enter the results of a simulation (from software such as EcoTect) in order to compute the fuel cycle burdens and factor them into the overall results.

The software compares material assemblies across a set of five environmental indicators:

- -Embodied primary energy (proxy for fossil fuel use)
- -Global warming potential
- -Toxic releases to air
- -Toxic releases to water
- -Solid waste

Instead of combining the variables into one overall score, the ATHENA EIE software keeps the categories separate so that the designers can judge the relative importance of variables.[30] For example, the proximity of a site near a critical water source gives greater importance to the "toxic releases to water" category. An example of a generated wall assembly comparison is shown in Figure 15.

TABLE 1: Wall assembly comparison

Assembly Type	Primary Energy per SF (MJ)	GWP per SF (kg)	Solid Waste per SF (kg)	Air Pollution Index
Window system with aluminum frame Low-E silver, argon-filled glazing	622.17	622.17	17.08	10.08
CIP Concrete, brick classind 2" extruded, 6mil PET 1/2" gypsum board, latex paint	237.93	237.93	2.81	1.63
CIP Concrete, stucco cladding 2" extruded polystyrene, 6mil PET 1/2" gypsum board, latex paint	160.23	160.23	3.29	2.39
Steel stud, stucco cladding 5/8 gypsum sheathing 3.5" fiberglass (batt), 6mil PET 1/2" gypsum board, latex paint	90.73	90.73	1.04	1.05

TABLE 2: Window frame comparison with clear double glazing

Window Type	Primary Energy per SF (MJ)	GWP per SF (kg)	Solid Waste per SF (kg)	Air Pollution Index
Window with aluminum frame	622.17	31.32	17.08	10.08
Window with PVC-clad wood frame	387.61	27.81	2.52	7.06
Window with PVC frame	513.77	36.95	2.90	9.24
Window with wood frame	345.69	23.13	4.60	6.24

Fig. 15 ATHENA EIE wall assemply comparison. GWP = Global Warming Potential.

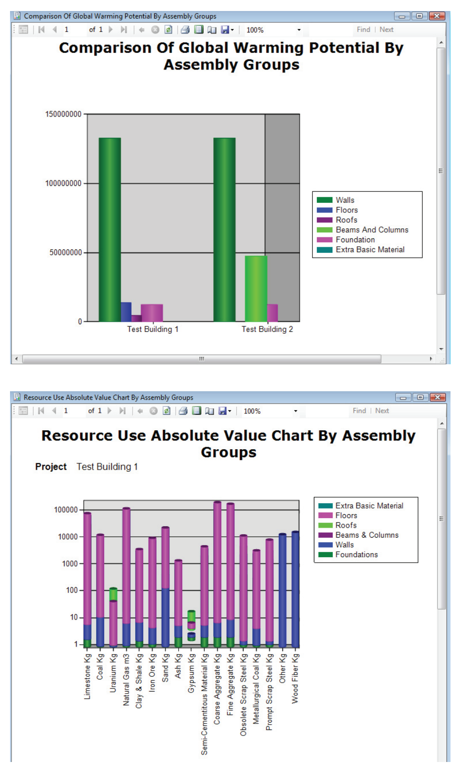

Fig. 16 Results calculated by ATHENA EIE software.

The comparison of assembly systems can scale up to entire buildings, allowing designers to compare parallel schemes to determine the highest performing solution. (Fig. 16) This high level of compound variable calculation was not possible to achieve quickly before the availability of LCI software.

The ATHENA EIE software benefits from having a ten-year pedigree. The U.K. has been using the Building Research Establishment's BRE Green Guide to Specification software with great success and the ATHENA EIE software models itself after this. Covering the environmental impacts of over 400 common building assemblies in low and high-rise categories, the ATHENA EIE software has a wide knowledge base to building upon. An example of building assemblies and their associated life cycle impact. [31]

Product Influence

The utilization of LCA to determine the most appropriate building assembly has had influence not only on the designers who specify material, but also on the scientists who create the material. For example, PVC roofing was generally accepted as a superior roofing system for its durability and insolation reflectance. However, when examined throughout its life, it shows that it requires a chemically harmful process to create and is difficult to dispose of properly after the life of the building. With consumers (and designers) now aware of this, the manufacturers were motivated to created a less harmful building system with that met

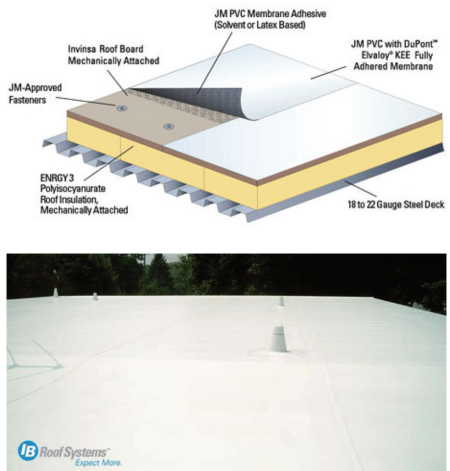

Fig. 17 Typical PVC roof system and the new IB Roof System.

the same performance criteria. The IB Roof System utilizes a plastic that is not as harmful as PVC but meets the same performance criteria.[32]

Material Quantification with BIM

Building Information Modeling (BIM) software makes the task of indexing entire building components possible. With BIM, buildings are created as a virtual prototype inside the computer. Instead of drawing unintelligent lines, building components with associated data are placed in the virtual model. BIM software is always aware of the amount of the different types of building components, which is a task insurmountable for humans alone to accomplish. This database of building components can be input into the ATHENA EIE system to identify opportunities in building assemblies.[33]

The performance of the virtual model of the building can be evaluated by Ecotect software, and this data can be combined with the material data to give the designer the result of not just material combinations but material and building performance combinations for an overall life cycle view. This combination of software allows the designer to rapidly test different schemes with tangible data to design a building that performs not only well in the short term but also over the life of its use.

Conclusion

Life cycle assessment is critical to building sustainable communities. Despite this necessity, market and cultural forces currently view LCA as being outside of the building scope. Innovations in BIM, BES, and LCI database software allow designers to virtually build and test their buildings before physically committing to their designs. For the first time, this allows designers to measure and foresee the ecological impact of potential building schemes.

As we monitor the impact of our buildings throughout their lifecycle, we will gain a greater understanding of the ecological implications of how we build. This will inform the subsequent generations of materials, mechanics, and buildings for the purpose of less ecological impact.

The transformation of sustainable design from hopeful nobility to measured accountability allows performance metrics to be defined with the intent of regulating our total ecological impact of our built environment. Only when we look at the built environment as a whole and throughout its lifecycle can we truly gain an understanding of how to build sustainably.

Notes

1. Malin, Nadav, 8.

2. Scientific Applications International Corporation (SAIC), 1.

3. Ibid., 54

4. Ibid., 2.

5. Finnveden, G., et al.,1.

6. Russell, A., 1207.

7. Finnveden, G., et al., 2.

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